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OPTIMIZING FOREST MANAGEMENT UNDER DEPENDENT PRICE AND PRODUCTION RISKS : A MARKOV DECISION PROCESS APPROACH

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Abstract

In the forest sector, natural disturbances have impact on production and prices. Traditionally, these risks have been analysed separately. In our model, the production risk translates into a price risk through a quality loss. We consider that the stock of timber follows a Markov Decision Process (MDP) with the harvesting decision as a control variable. We solve the optimal harvesting problem under storm risk with a risk-averse forest owner and when risk induces triple dependent consequences on production, price and timber quality. We study the impact of the risk distribution, the risk aversion level and the percentage of quality loss on the optimal harvesting decision.

Introduction

As forest growth is a long planning period, considerable risks concerning the future state of the forest have to be dealt with. The main risks are due to natural disturbances such as wind damage and forest fire, that can also impact other sources of risk such as changes in market prices. **Storms** are the source of 53% of the total forestry damage due to natural hazards in the European forests (Schelhaas et al., 2003).

For example, in January 2009, Windstorm Klaus was responsible for around 40 millions of cubic meters of damages in the South-Western part of France. Moreover, the price of the damaged species decreased in 30% after the storm due to a quality loss (Nicolas, 2009).

Storms affect forest owners' management through their effects on production, prices and timber quality, that are interdependent. First, storms impact forest stocks (**production risk**). Second, storms force the forest owner to rapidly put windfalls in the market, generating a timber price decrease (**price risk**). Third, storms cause timber **quality loss** amplifying the price decrease. This triple consequence highlights the importance of forest owner's response to such risks.

Focusing on optimal stand management under growth and price risks, the first application of MDP to forestry by **Lembersky and Johnson (1975)** was followed by similar applications : Kao (1982), Teeter and Caulfield (1991), Lohmander (2000), Pastor et al. (2005). However, to the best of our knowledge, there is currently no method for optimizing a forest management under stochastic events using a MDP that also explicitly incorporate the link with timber price and timber quality.

Objective and contributions

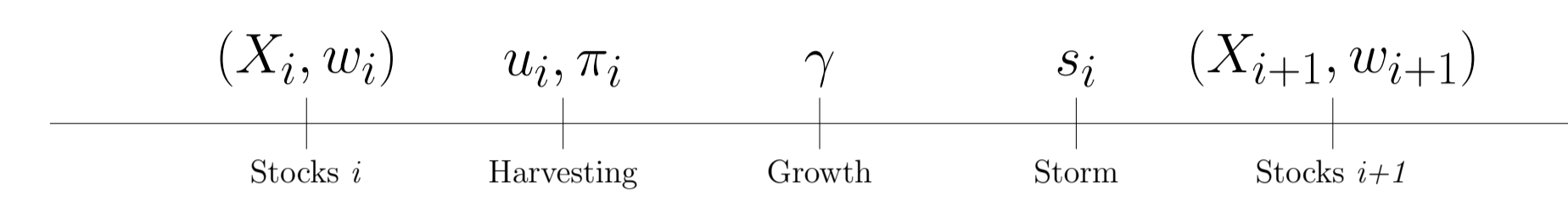
The objective of our paper is to analyse the impact of storm on forest owner's harvesting decision under dependent production and price risks amplified by a quality loss. We propose a Markov Decision Process (MDP) modeling framework to describe the timber stock dynamics and the forest owner's objective of expected intertemporal utility maximization.

In our work, four contributions can be underlined :

- Previous works consider that production and price risks are independent. We take into account that, for natural disasters, the **production risk translates into a price risk**
- We consider that the price risk is amplified by a **timber quality loss**
- Previous studies analyse the impact of production and price risks on the optimal harvesting age, while we focus on **timber harvesting**
- Traditionally, the forest owner is risk-neutral, while we consider **risk aversion**

The model

Timing : let us model a dynamic forest management process with an infinity of harvesting periods. Each period i is defined by the following sequence of events :



Timber stock : the evolution of timber stock, standing trees X_i and windfalls w_i , is as follows :

$$X_{i+1} = X_i - u_i + \gamma_i - w_{i+1}$$

with $w_{i+1} = \min[s_i, X_i - u_i + \gamma_i]$ and under the constraint $0 \leq u_i \leq X_i$.

Transition matrix : the probability of moving from one state of the stock to another one, conditional on the harvesting decision is :

$$P(X_{i+1}, w_{i+1} / X_i, w_i, u_i)$$

Price modeling : two different markets

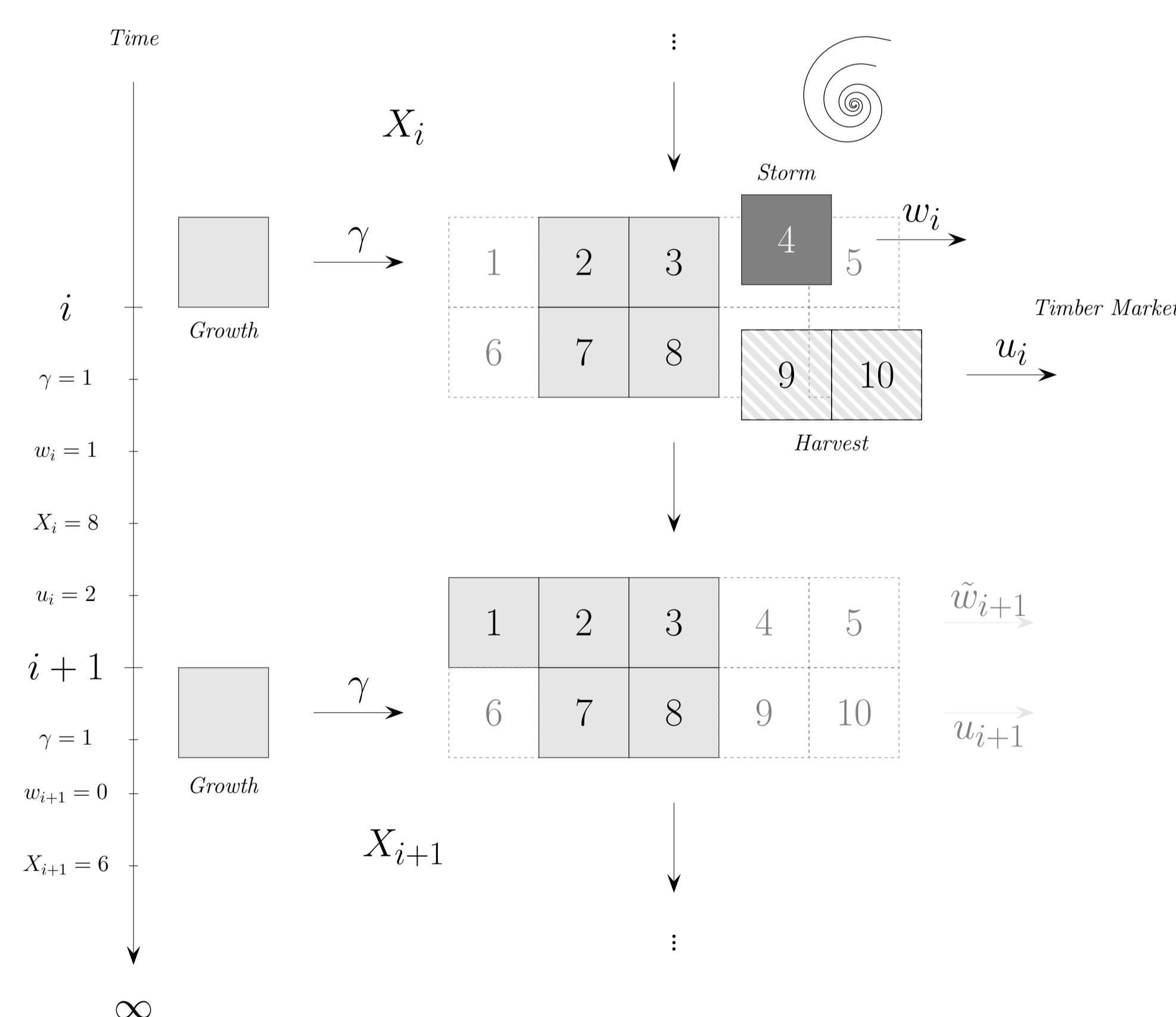
- Market for the harvesting of standing trees with a price p_t constant over time
- Market for the windfalls with a price $p_t^w = \alpha p_t - b w_i$
 $\rightarrow \alpha \in [0; 1]$ is a % of price p_t corresponding to the lower quality of fallen trees

Objective function :

- At each period, the forest owner's profit is : $\pi_i = p_t u_i + p_t^w w_i$
 - The expected intertemporal utility is : $\max_{u_i} E \left[\sum_{i=0}^{\infty} \frac{V_i}{(1+\lambda)^i} \right]$
 where λ is the discount rate and $V_i = \frac{\pi_i^{1-\beta}}{1-\beta}$ with β the relative risk aversion coefficient
- \Rightarrow Optimal harvesting policy u^*

Illustration

The following figure presents an example for transition from period i to $i+1$ for $N = 10$.



Stock X_i results from the dynamics of the previous periods, the growth and the storm, is composed of $X_i = 8$ portions (1 due to growth, 2, 3, 4, 7, 8, 9 and 10) among the $N = 10$ portions of the total stock X . Portions 5 and 6 are empty due to previous harvesting decisions or storms. The forest growth ensures that portion 1 is regenerated. Stock X_i is affected by a storm of intensity $w_i = 1$ resulting in a forced commercialization of portion 4. Added to this, the manager decides to harvest $u_i = 2$ portions (9 and 10) among available standing stock (1, 2, 3, 7, 8, 9 and 10). As a result, in period $i+1$, the remaining timber stock is composed of $X_{i+1} = 6$ portions (1, 2, 3, 6 due to growth, 7 and 8) since, in this example, $w_{i+1} = 0$.

Results

The following table contains the optimal harvesting decision u for each pair of state variables : stock of standing trees (rows) and stock of windfall (columns). In parenthesis appears the expected intertemporal utility.

Assumptions : $N = 10$, $\gamma = 1$, $p_t = 1$, $\alpha = 1$, $\lambda = 0.05$, $\beta = 0.5$, $P = (0.3, 0.212, 0.15, 0.106, 0.075, 0.053, 0.037, 0.026, 0.019, 0.013, 0.009)$.

Standing stock (X_i)	Windfall (w_i)				
	0	1	2	3	4
0	0 (28.3)*	0 (30.1)	0 (30.7)	0 (31.1)	0 (31.3)
1	1 (30.2)	1 (21)	0 (31.5)	0 (31.9)	0 (32.1)
2	1 (31)	1 (31.8)	1 (32.2)	1 (32.5)	1 (32.6)
3	2 (31.8)	2 (32.4)	2 (32.7)	2 (33)	2 (33.1)
4	3 (32.4)	3 (32.9)	3 (33.2)	1 (33.5)	1 (33.6)
5	4 (33)	4 (33.3)	2 (33.7)	2 (34)	1 (34.1)
6	3 (33.4)	3 (33.9)	2 (34.2)	2 (34.5)	2 (34.6)
7	4 (33.9)	3 (34.4)	3 (34.7)	2 (34.9)	2 (35)
8	4 (34.4)	3 (34.8)	3 (35.1)	3 (35.4)	3 (35.5)
9	4 (34.9)	4 (35.3)	2 (35.6)	2 (35.8)	2 (36)
10	5 (35.3)	3 (35.7)	2 (36)	2 (36.3)	2 (36.4)

* Timber harvesting u (expected intertemporal utility)

Boxed element : stock of standing trees is $X_i = 4$ and there is no windfall $w_i = 0$. The corresponding optimal harvesting is $u_i = 3$ units of trees and to keep one unit standing. The forest owner's expected intertemporal utility is 32.4.

Sensitivity analysis

Sensitivity analysis is carried out for three parameters : risk distribution, risk aversion coefficient and quality loss. Such an analysis is driven by three effects :

- **Wealth effect** derives from the harvesting revenue : the higher the harvesting, the higher the revenue (incentives to harvest)
- **Risk effect** driven by the tendency of owner to reduce the risk exposure of the forest : the higher the risk, the higher the harvesting (incentives to harvest)
- **Continuation effect** : harvesting reduces timber stock at the beginning of the next period which lowers utility (incentives to not harvest)

Conclusion

We have developed a **MDP model** for forest management under storm risk and proposed a tool for finding the optimal harvesting policy that shows coherent behaviors :

- Increasing (decreasing) **storm risk** leads the forest owner to harvest more (less) and lowers (increases) the expected intertemporal utility.
- Increasing (decreasing) **risk aversion** leads the forest owner to harvest less (more) and raises (reduces) the expected intertemporal utility.
- Increasing **quality loss** has no effect on harvesting and decreases expected intertemporal utility.

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